Seismic Monitoring Techniques Put to a Test

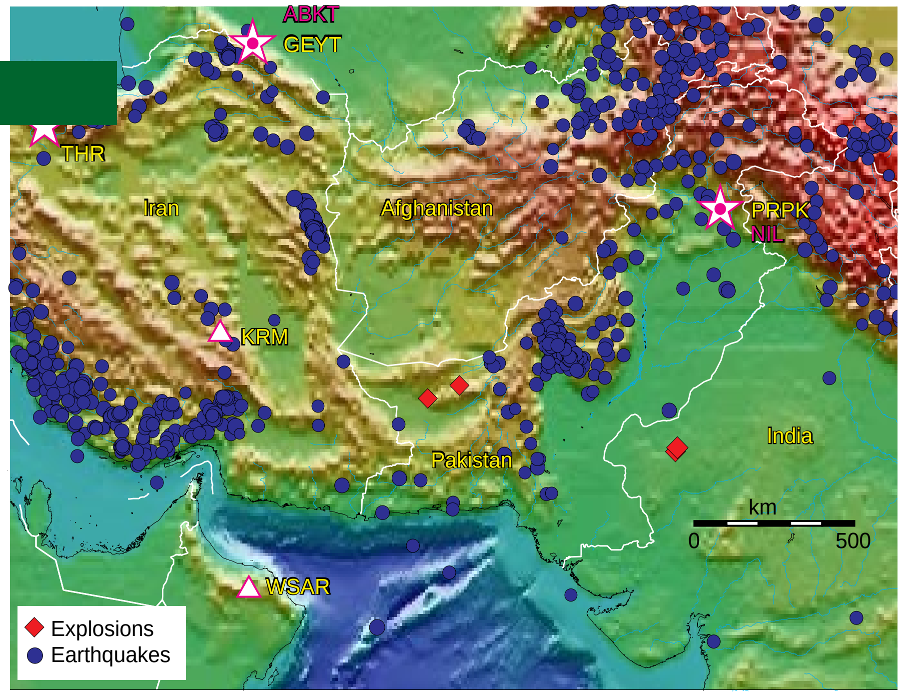

Figure 1. Topographic map showing the locations of the Indian nuclear tests in 1974 and on May 11 and 13, 1998, the Pakistani nuclear tests on May 28 and 30, 1998, and earthquakes recorded in the region between 1995 and 1997. Also shown are the planned locations of the International Monitoring System's primary (stars) and auxiliary (triangles) seismic stations and the Incorporated Research Institutions for Seismology's stations closely collocated at Alibek, Turkmenistan (ABKT), and Nilore, Pakistan (NIL).

WHEN the world received the news of the Indian and Pakistani clandestine underground nuclear tests last May, a team of Livermore researchers used the events to validate several seismic methods they have developed over the past decade to monitor the Comprehensive Test Ban Treaty (CTBT). Using data recorded worldwide by a host of seismic monitoring stations, the team successfully differentiated the nuclear blasts from typical regional earthquakes, characterized the yields of the tests, and noted inconsistencies between the announced test yields and the seismic data. In all, the seismic signals from the nuclear tests provided important new data to help calibrate seismic stations in a critically important region of the world.

The CTBT has been signed by 152 nations, although not by India or Pakistan. The treaty provides for an International Monitoring System (IMS) of automated seismic stations, many of them still to be installed, to record any evidence of clandestine nuclear explosions. These stations transmit data via satellite to the International Data Center in Vienna, Austria, which in turn distributes them to national data centers around the world. Figure 1 shows the location of existing seismic stations in the Southwest Asia area, planned IMS seismic stations, the seismically determined locations of the recent tests by India and Pakistan, and locations of some recent earthquakes in the region.

The U.S. Department of Energy is supporting the U.S. National Data Center (USNDC) at Patrick Air Force Base, Florida, as it prepares to monitor the treaty. As part of DOE's effort, teams at Livermore and Los Alamost have been working to improve ways to seismically characterize clandestine underground nuclear explosions and differentiate them from other sources of seismicity, such as earthquakes and mining explosions. Much of Livermore's work has centered on developing regional discriminants, which are characteristic features of a seismic waveform (for example, the peak amplitude at a particular frequency, within a specific time frame) recorded at distances less than 2,000 kilometers away. These discriminants are used to differentiate between explosions and other types of seismic sources. (See the September 1998 *Science & Technology Review*, "Forensic Seismology Supports the Comprehensive Test Ban Treaty," pp. 4–11.)

India's nuclear test took place on May 11 and 13, 1998, followed by Pakistan's on May 28 and 30, 1998. None of the planned IMS seismic stations in the region was installed at the time of the tests. Fortunately, stations belonging to IRIS (Incorporated Research Institutions for Seismology), a consortium of U.S. universities, were operating. Two of those stations, called ABKT, in Alibek, Turkmenistan (one of the former Soviet republics), and NIL, in Nilore, Pakistan, were near the sites of two proposed IMS stations GEYT and PRPK. While ABKT data were not available, NIL records of the Indian tests, some 740 kilometers away, were available through the Internet within a few hours, as were data provided by IRIS for other stations throughout the world. The NIL station was turned off during the Pakistan tests, so the data were unavailable.

As part of their calibration work for the USNDC, the Livermore seismologists had already collected and analyzed data recorded by NIL and other seismic stations from more than 200 regional earthquakes between 1995 to 1997 in Iran, Afghanistan, Pakistan, western India, and the surrounding

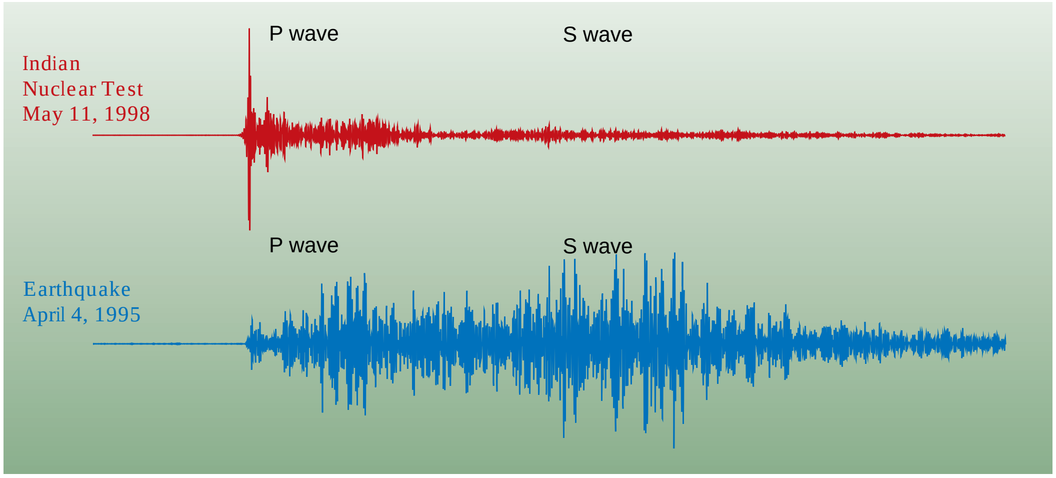

Figure 2. Seismograms of the Indian nuclear test (top) and a representative nearby earthquake (bottom) recorded at the seismic station at Nilore, Pakistan. These seismic signatures for an explosion and earthquake are typical and clearly distinguish one from the other.

region. Within hours of the announcement of the May 11, 1998, Indian tests, Livermore seismologists were comparing its seismogram with those from nearby earthquakes.

As seen in Figure 2, the seismogram from a representative earthquake clearly differs from that of the May 11 test. Livermore-refined discriminants based on P and S waves were strongly indicative of an explosion, not an earthquake or other seismic source, at all frequencies tested (0.5 to 8 hertz). Livermore seismologist Bill Walter explains that the differences in seismic P- and S-wave energy provide one method of discriminating explosions from earthquakes. Seismic P waves are compressional waves, similar to sound waves in the air. Shear (S) waves are transverse waves, like those that propagate along a rope when one end is shaken. Because underground explosions are spherically symmetric disturbances, they radiate seismic P waves efficiently. In contrast, earthquakes result from sliding or rupture along a buried fault surface and strongly excite the transverse motions of S waves. Thus, we expect that explosions will show strong P waves and weak S waves and that earthquakes will show weak P waves and strong S waves, as seen in Figure 2.

According to Walter, one way to quantify this difference is by determining the ratio of P-wave to S-wave energy measured from the seismograms. Explosions should have higher P/S ratios than earthquakes, but the frequency at which the best separation occurs varies by region and station. Figure 3 shows the P/S ratio for the May 11 Indian test and for earthquakes shown in Figure 1. The measurements in Figure 3 were made at four different frequencies. The Indian test has a higher P/S ratio than the earthquakes, as expected.

India reported that its nuclear testing on May 11, 1998, was composed of three almost simultaneous explosions with yields of 45, 15, and 0.2 kilotons and that the two larger tests were separated by about a kilometer. According to Walter, the team's examination of regional data recorded at NIL and at teleseismic stations thousands of kilometers away did not reveal obvious signs of multiple shots. The U.S. Geological Survey reported a teleseismic magnitude of mb 5.2 (mb is the bodywave magnitude and is roughly related to the Richter scale). Assuming simultaneous detonation of the three tests and using published magnitude–yield formulas for a stable region, the announced total yield of 55 to 60 kilotons appears to be at least three times larger than the yield indicated by the seismic data.

Livermore researchers then compared the seismogram from the May 11, 1998, tests with India's May 18, 1974, single test (its only previous nuclear test) using data from stations in Canada and Scotland that recorded both events. The 1974 test generated a clearly detected teleseismic signal with an mb of 4.9. Because India declared the 1974 explosion a "peaceful nuclear explosion," some information about it was reported, such as the fact that it was a single explosion at a depth of 107 meters. However, Indian scientists and officials stated a large range in the yield estimate—4 to 12 kilotons.

Figure 4 shows the seismograms from the 1974 and 1998 tests using data from the Canadian station (for ease of comparison, the 1974 test's amplitude is doubled to match that of the 1998 test.) The two seismic waveforms show remarkable similarity.

Several interpretations of the seismic observations are possible. According to Livermore seismologist Arthur Rodgers, if the three 1998 shots were indeed detonated nearly simultaneously and separated by less than a few kilometers, "We would probably see just one large shot in the seismic waves." Rodgers also says that the second and third shots could have been so small compared to the first that they were overwhelmed in the seismogram. Also, a cavity or substantial amount of porous material near the explosive site could, if present, have reduced the coupling of energy into seismic waves, thereby significantly reducing the seismic magnitude of all three tests. Finally, it is possible that the yield announced by the Indian scientists was simply three to six times too large.

On May 13, India announced two additional low-yield tests totaling 800 tons. The Livermore team examined data

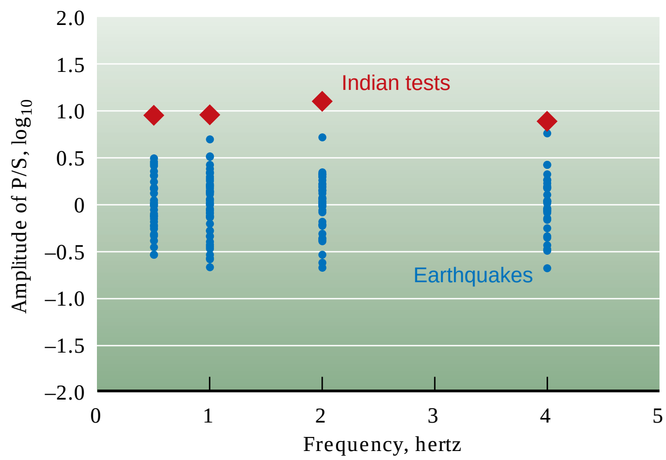

Figure 3. P-to-S amplitude ratios versus frequency for the Indian nuclear test (diamonds) and nearby earthquakes (circles). Note that the P- to S-wave ratios are higher for the Indian test than for the earthquakes.

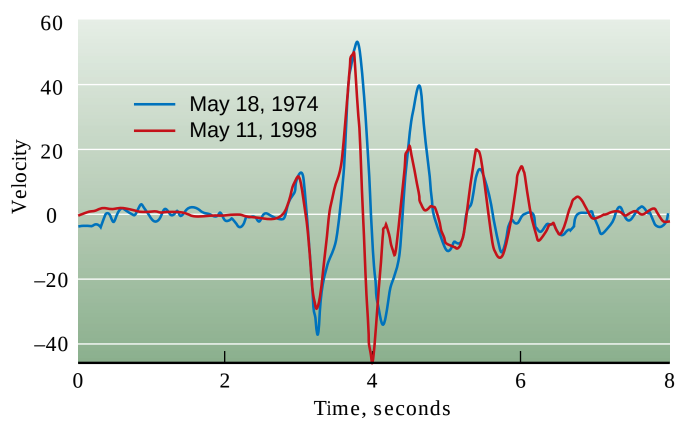

Figure 4. Signals from the 1974 and 1998 Indian underground nuclear tests recorded in northern Canada. (To make the similarities more apparent, the amplitude of the May 18, 1974, data has been doubled.)

provided by the NIL station, but none showed any obvious seismic signal. Using the largest amplitude of the background earth noise around the time of the test as an upper bound for the signals from the event, the Livermore researchers determined that the event must have produced an mb of less than 2.8. The two tests were said to be conducted in a sand dune, which might poorly couple the explosive energy into seismic waves and thus reduce the strength of any recorded seismic signal. Adjusting for this geologic condition, says Walter, a signal should have been observable at NIL if the yield was 100 tons or more.

Walter says that the nuclear tests in India provided valuable data in a region with only a single previous nuclear test. This data will be used to help calibrate the CTBT monitoring network.

The data from the Indian tests will also improve scientists' understanding of the physical basis of the regional discriminants developed at Livermore. As a result of the tests, the discriminants may be applied with greater confidence to much lower yield explosions than the Indian tests and in South Asia and other regions where no nuclear test data are available to calibrate nearby monitoring stations.

The Livermore team plans to conduct more research to further characterize the May events as additional seismic data and information on emplacement conditions become available from Indian and Pakistani officials and scientists. In the meantime, researchers are hopeful that their detailed analysis of the nuclear tests, done without the forthcoming IMS stations, shows that the planned international network will indeed be effective in detecting and identifying clandestine nuclear tests.

—Arnie Heller

Key Words: Comprehensive Test Ban Treaty (CTBT), discriminants, U. S. National Data Center (USNDC), nuclear test.

For further reading:

W. R. Walter, A. J. Rodgers, K. Mayeda, S. Myers, M. Pasyanos, and M. Denny, *Preliminary Regional Seismic Analysis of Nuclear Explosions and Earthquakes in Southwest Asia*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-JC-130745, July 1998.

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Sleuthing MTBE with Statistical Data

METHYL tertiary-butyl ether, more commonly known as MTBE, is a chemical Janus. It benefits air quality by making gasoline burn cleaner, thus reducing automobile emissions. But it can also find its way into groundwater supplies and give drinking water an unpleasant taste and odor. At present, more than 20 public drinking water wells in California have ceased water production for this reason. Worse yet, the health effects of MTBE are uncertain—the U.S. Environmental Protection Agency currently classifies MTBE as a possible human carcinogen.

Since 1992, MTBE has been the compound of choice for U.S. oil refineries required by the federal Clean Air Act to add an oxygenate to gasoline to help reduce air pollution. However, some MTBE has appeared in drinking water wells throughout the U.S. This discovery has sparked a national controversy between the need to reduce air pollution (especially in heavily populated areas) and the necessity to safeguard precious water resources from contamination. In an effort to resolve this controversy, the U.S. Environmental Protection Agency (EPA) formed a 14-member panel of MTBE experts from government, the oil industry, academia, regulatory agencies, and environmental groups to explore the environmental and public health effects of MTBE and make policy recommendations by July 1999.

Anne Happel, an environmental scientist at Lawrence Livermore, is a member of this EPA blue-ribbon panel. She leads a multidisciplinary team in the Environmental Restoration Division studying MTBE contamination of groundwater from leaking underground fuel tanks (LUFTs) throughout California. The team's goal is to help water quality regulators, public health specialists, and MTBE users understand more about how MTBE enters and behaves in groundwater so they can better manage its use, prevent harm to humans, and protect limited groundwater resources. The team has estimated how often MTBE escapes into groundwater through gasoline release and traced the behavior of MTBE in groundwater. The team is currently designing a data management system to target LUFTs most in need of remediation because of the risk they present to drinking water sources. The database will allow those responsible for water quality to better manage the cleanup of leaking tank sites and strategically protect drinking water from MTBE.

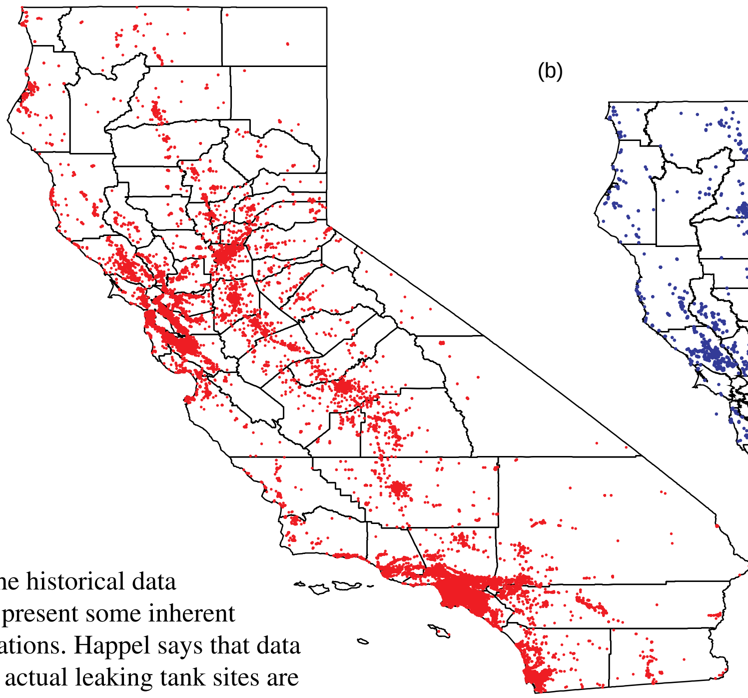
The study results to date have provided the project sponsors—the California State Water Resources Control Board, the U.S. Department of Energy, and the Western States Petroleum Association—with fundamental information for effective management of California's groundwater resources. They will also be used to help make legislative decisions and set policy regarding MTBE's use as a gasoline additive in California and nationwide.

Analyzing Field Data

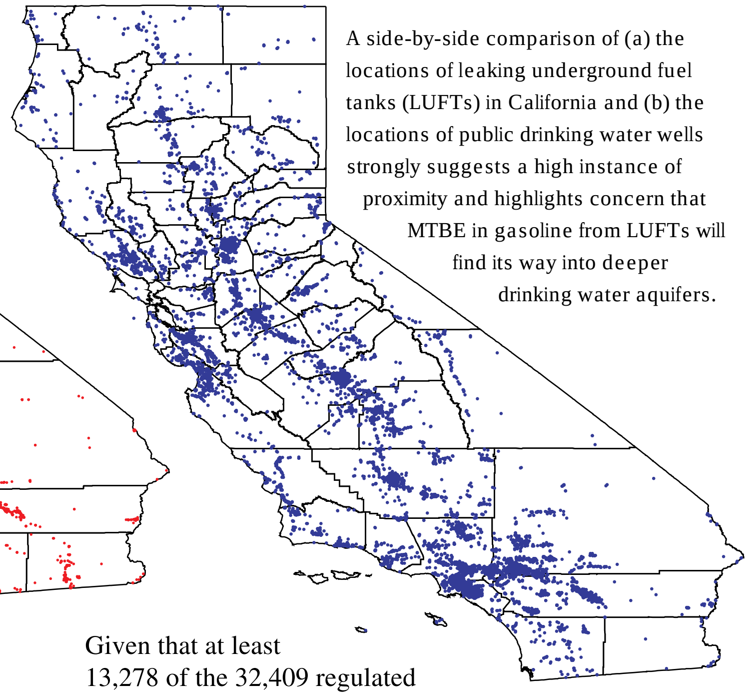
Scientists know that MTBE behaves differently in groundwater from other petroleum products such as benzene. Unlike petroleum hydrocarbons, it is highly water soluble, not easily adsorbed to soil, and resists biodegradation. Thus, with widespread use, MTBE has the potential to occur in high concentrations in groundwater, travel far from leak sources, and accumulate to become a hazard on a regional scale.

To investigate these potentialities, the Livermore project team designed a study of MTBE subsurface plumes based on statistical analysis of historical data from California LUFT sites. Researchers investigated data collected at leaking tank sites throughout California to gain insight into MTBE movement from actual gasoline releases. They examined the frequency of MTBE contamination of groundwater at LUFT sites and public water wells throughout California and analyzed the behavior (mobility and attenuation) of MTBE plumes as compared to benzene plumes at LUFT sites.

(a)



(b)



A side-by-side comparison of (a) the locations of leaking underground fuel tanks (LUFTs) in California and (b) the locations of public drinking water wells strongly suggests a high instance of proximity and highlights concern that MTBE in gasoline from LUFTs will find its way into deeper drinking water aquifers.

The historical data used present some inherent limitations. Happel says that data from actual leaking tank sites are filled with real-world complexity, uncertainty, and variability. For example, a leaking tank site may have had multiple past releases, each formulated with different quantities of MTBE; the ages of the releases are also unknown; and estimates of their volume are uncertain.

When natural variability is added into the analyses—for example, MTBE transport can vary in different geologies, or it can fluctuate because of the elevation and gradient of the groundwater surface—it is easy to see that data from these sparsely monitored individual sites are less than ideal for precise, quantitative contaminant transport research, which relies on data from large, heavily monitored sites. The project team overcame some of these limitations by treating data from a large number of sites as a statistical population. Similar to an epidemiological survey, this approach allowed them to deduce general trends in the behavior of MTBE and other petroleum hydrocarbons.

The first data analyzed were from 236 LUFT sites located in 24 counties where groundwater had been monitored for MTBE prior to the beginning of 1996, earlier than legally required. The Livermore team began by assessing how well standard Environmental Protection Agency analytical methods (EPA 8020 and EPA 8260) performed for detection and quantification of MTBE in groundwater samples in the presence of dissolved gasoline. This evaluation enabled the team to quantify the margin of error in the historical data collected using the EPA methods so that the data could be interpreted, presented, and used with appropriate caveats and qualification.

The project team found that the groundwater of 78 percent of these 236 sites contained detectable levels of MTBE. Given that at least 13,278 of the 32,409 regulated LUFT sites are known to have contaminated groundwater, the project team inferred that more than 10,000 LUFTs may have released MTBE into groundwater. These conclusions are consistent with recent work in which data were collected from over 4,000 sites throughout California.

The Conclusions They Reached

While the inferred 10,000 sources of MTBE contamination were the focus of journalistic reporting on MTBE problems, that number was an estimate of the extent of contamination and only one of the findings from the overall investigation. The project team also measured MTBE plume lengths and compared them with the lengths of benzene plumes—benzene is currently the petroleum compound of greatest regulatory concern—to determine the overall plume migration of the two compounds. Finally, team members analyzed the behavior of MTBE groundwater plumes over time. They were fortunate to obtain MTBE data for 29 sites in San Diego County collected since the beginning of 1992 by an oil company that had analyzed for MTBE while sampling for other hydrocarbons.

The team's work confirmed and quantified what other informal, piecemeal studies had hypothesized, namely, that MTBE is a frequent and widespread contaminant in shallow groundwater throughout California, that MTBE plumes are more mobile than hydrocarbon plumes, and that MTBE may attenuate primarily through dispersion because it resists biodegradation.

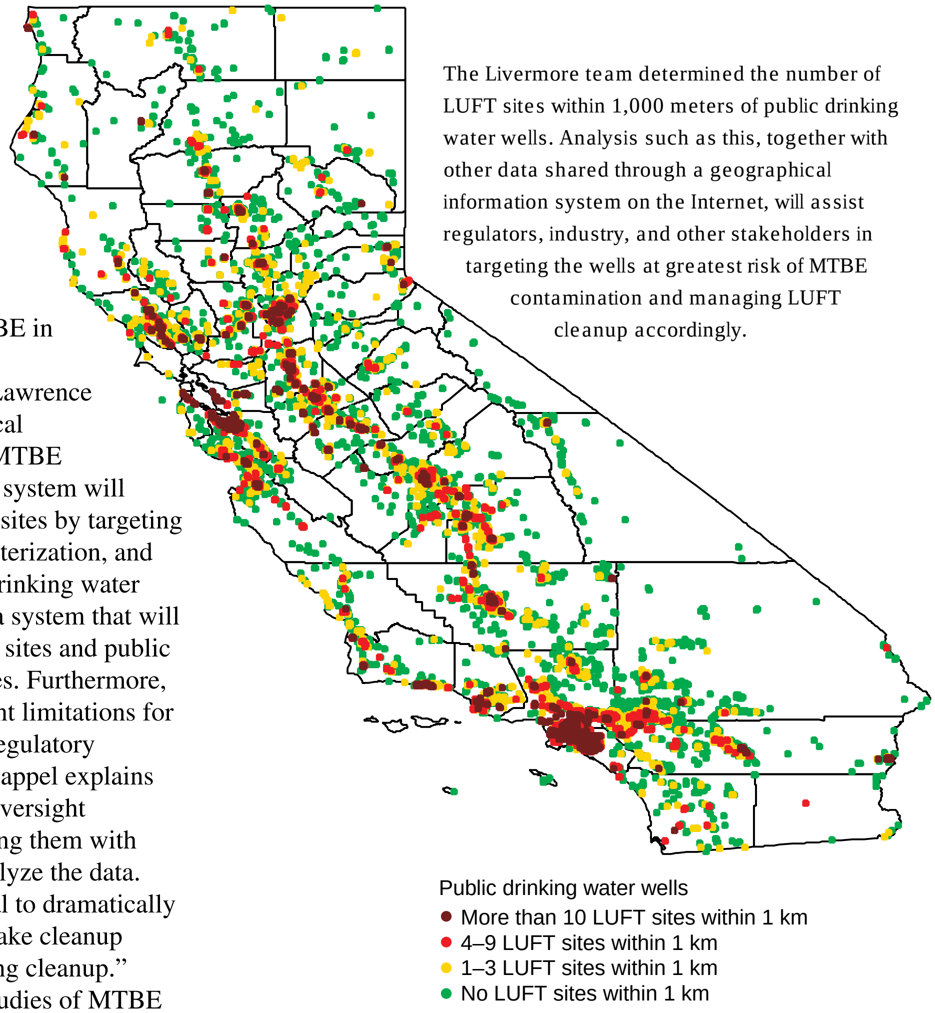
Put together, these conclusions point to a compound that may progressively accumulate until it contaminates groundwater resources on a regional scale. The team's findings substantiate the need for MTBE regulation and help provide the initial regulatory boundaries.

More Insights to Come

Given the widespread distribution of MTBE in groundwater at leaking tank sites throughout California, the State Water Board is asking Lawrence Livermore to develop a statewide geographical information system to manage the threat of MTBE contamination to public water supplies. This system will allow regulators for the first time to "triage" sites by targeting manpower and resources for analysis, characterization, and remediation of leaking tank sites closest to drinking water supplies. The Livermore team has designed a system that will provide detailed information on leaking tank sites and public water supplies to multiple regulatory agencies. Furthermore, access over the Internet will overcome current limitations for obtaining and sharing data among multiple regulatory agencies, industry, and other stakeholders. Happel explains that the goal is to give all interested parties oversight management of leaking tank sites by providing them with access to LUFT data and on-line tools to analyze the data. "We believe that this system has the potential to dramatically transform the way regulators and industry make cleanup decisions and establish priorities for managing cleanup."

The team also will be performing more studies of MTBE biodegradation. All the while, it will be leveraging information and technologies from other projects in Livermore's Environmental Restoration Division to further its MTBE work. The team's insights will be valuable contributions to revising MTBE regulations.

—Gloria Wilt



The Livermore team determined the number of LUFT sites within 1,000 meters of public drinking water wells. Analysis such as this, together with other data shared through a geographical information system on the Internet, will assist regulators, industry, and other stakeholders in targeting the wells at greatest risk of MTBE contamination and managing LUFT cleanup accordingly.

Key Words: gasoline releases, geographical information system, groundwater, leaking underground fuel tanks (LUFTs), methyl tertiary-butyl ether (MTBE), statistical analysis, water quality.

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